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A NEW METHOD FOR MEASURING THE CRITICAL CHARACTERISTIC CURVES OF SUPERCONDUCTORS

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ABSTRACT

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A persistent-current method for measuring the critical characteristic curves of superconductors is described. Compared with the usual four-probe method, the new method claims the following advantages: 1) The physical significance of the curves thus determined for $I_c(H)$ becomes clear; 2) the technical difficulty of introducing a large current into the cryostat is avoided; 3) there is no danger of burnout of the specimen tested. The $I_c(H)$ curve for cold-worked niobium wire is determined with this method. The result confirms the existence of the peak previously observed with the four-probe method in the $I_c(H)$ characteristic. author

I. INTRODUCTION

The dependence of the critical current I_c of a superconductor on the external magnetic field H at constant temperature is normally called the critical characteristic, or $I_c(H)$ curve, of the superconductor.

The need for measuring the critical characteristic curve is emphasized by the following considerations:

1. In designing superconducting magnets, it is required to obtain information regarding the $I_c(H)$ curve of the superconducting material (refs. 1 and 2).

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*Numbers in the margin indicate pagination in the original foreign text.

It was, in fact, after the first discovery of certain superconducting materials possessing suitable $I_c(H)$ curves that strong magnetic fields began to be generated with superconductors (refs. 3 and 4).

2. The characteristic $I_c(H)$ curve not only depends on the temperature and composition of the specimen, it is also sensitive to the structure of the material. The amplitude and shape of the curve are significantly affected by cold working and heat treatment of the specimen (refs. 5 and 6). The investigation of the dependence of the $I_c(H)$ curve on the state of the specimen is important insofar as understanding the mechanism of the loss of superconductivity in hard superconductors. For example, in studying the effects of partial phase separation of Pb-Sb alloys on the $I_c(H)$ curve (ref. 7), we arrived at the following important conclusion: A high-field superconductor must simultaneously have a small electron mean free path and appreciable inhomogeneity.

Until now, the four-probe method has normally been used to measure the critical curves of superconductors (ref. 8). The specimen is held in a constant magnetic field and the input current to the specimen is gradually increased (or, alternatively, the specimen is imparted a constant current and the field is gradually increased) until a measurable potential drop (usually assumed to be from 10^{-9} to 10^{-7} V) develops between the potential probes. This condition is adopted as a point on the critical characteristic curve for the specimen.

The $I_c(H)$ curve so defined does not have a clear physical interpretation. First of all, it rests on the arbitrary choice of "smallest measurable potential difference" (ref. 9). Moreover, no matter how small a potential difference is decided upon, the states indicated on the curve all imply that continuous superconducting paths no longer exist in the specimen. Thus the value of $I_c(H)$ is actually greater than the maximum admissible superconducting current (critical current). Second, after the smallest observable potential difference has been chosen, $I_c(H)$ will still depend on the size and shape of the specimen. For example, in the case of specimens having the same diameter, long ones will have smaller values of $I_c(H)$ than short ones. Even more important, the physical states on different segments of an $I_c(H)$ curve obtained by the four-probe method are not analogous. In the weak field region, the critical current is very large; the state corresponds to the onset of a very small electrical resistivity in the specimen. The situation is exactly reversed in the strong /890 field region. Since the critical current is small, it is necessary for the resistivity of the specimen to become sufficiently large before the potential drop across the specimen will attain the same observable value as the high-I_c case.

There are also technical difficulties in the four-probe method. Some specimens have critical currents as high as tens or hundreds of amperes. Without special means, it is difficult to deliver such high currents into the cryostat. Moreover, when the specimen has a relatively high $I_c(H)$ value, it usually burns out after the superconductivity is lost and cannot be used for further measurement. Consequently, in a great many investigations (refs. 7, 8, and 10), only a portion of the $I_c(H)$ curve has been determined (namely, the small I_c portion).

The present paper outlines a new method for measuring the critical characteristic curves of superconductors. It essentially circumvents the difficulties inherent in the four-probe method. We first describe a current source capable of delivering large currents at liquid helium temperatures. We then introduce a method for measuring the $I_c(H)$ curve and the results of such a measurement on a cold-worked niobium wire. It turns out that the current source we have designed may also be used as a device for continuously varying the frozen-in flux.

II. A CONTINUOUSLY ADJUSTABLE PERSISTENT CURRENT SOURCE

1. Experimental Apparatus

By moving a permanent magnet we create a persistent current in a closed superconducting circuit and use it as the current source for measuring the $I_c(H)$ curve of a superconducting specimen.

The experimental apparatus is shown in figure 1. The upper and lower niobium coils 2 and 6 form a closed circuit. A cylindrical Alnico-5 permanent magnet 1, which forms the current source, is placed in the upper coil. The permanent magnet can be moved along the axis of the coil, thereby varying the magnitude of the persistent current in the circuit.

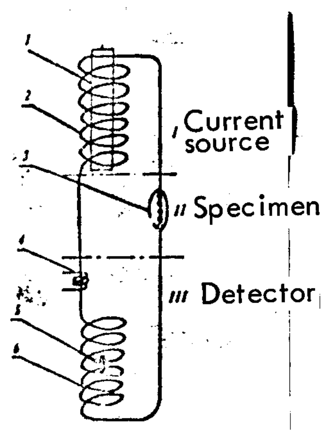

Figure 1. Schematic Diagram of the Current Source.

1) Permanent Magnet; 2) Upper Nb Coil; 3) Nb_3Sn Contact; 4) Heater Wire; 5) Bismuth Resistor and Detector Coil; 6) Lower Nb Coil.

A pickup coil and bismuth wire resistor 5 for measuring the field induced by the generated current are placed in the lower coil. The magnitude of the persistent current can be determined from the field-current curve of the lower coil. A manganese-copper wire heating element 4 is used to destroy the local superconductivity of the circuit. The wire is 0.1 mm in diameter and is wound around a piece of niobium wire connecting the two coils. The thermal power for destroying the superconductivity is 0.8 W. The lower coil, bismuth wire resistor, pickup coil, and manganese-copper heating element form the current detector section of the apparatus.

The specimen 3 is connected in series with the Nb wires attached to the two coils. In order to study the operation of the current source, we omitted the specimen in the experiment described in this section. We applied heat to coat 30 mm on the two ends of the Nb wires with a thin layer of Sn, twist them together, then fuse them in a vacuum of 10^{-5} mm Hg at about 950°C for one to three minutes. The Nb_3Sn connection thus created was further coated with In-Sn alloy to ensure the superconductivity of the contact and a larger critical current than that of the Nb wire or of the specimen.

The brass cores of the upper and lower coils were the same size (fig. 4). They had an inside diameter of 0.8 mm and were wrapped with paper for insulation. The upper and lower coils had 169 and 174 turns, respectively. The permanent magnet had a diameter of 10 mm and a length of 56 mm. The device on top of the Dewar flask for controlling the vertical motion of the permanent magnet was capable of producing a 60 mm displacement. When magnetized at room temperature, the magnet had a saturation magnetic induction of 11 000 G.

During the experiment, the entire apparatus was placed in a cryostat filled with liquid helium.

2. Experimental Results and Discussion /891

In the first few trials, the permanent magnet was placed in the initial position as shown in figure 1, prior to the transference of liquid helium into the cryostat. After the cryostat had been filled with liquid helium, the Nb coil "froze in" the flux supplied by the permanent magnet. Then, when the permanent magnet was gradually raised out of the upper coil, a persistent current was excited in the Nb coils due to the conservation of flux in the superconducting circuit. From the detector in the lower coil, it was possible to observe a gradual increase in the resistance of the bismuth, consistent with the increase in field strength.

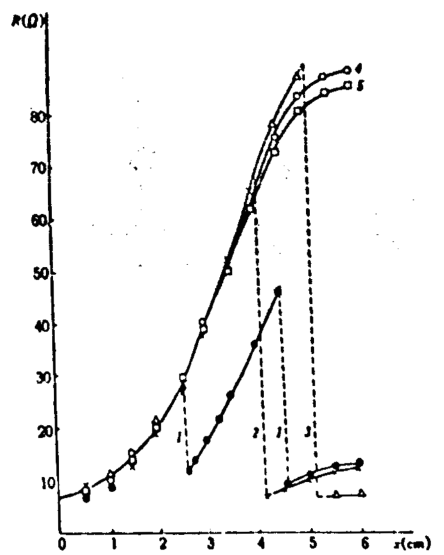

Figure 2. Variation of the Bismuth Resistance in the Lower Coil as the Permanent Magnet is Raised Upward.

o - First Test; x - Second Test; Δ - Third Test; o - Fourth Test; ▫ - Fifth Test.

The results are shown in figure 2. The resistance of the bismuth is plotted on the vertical axis, the distance by which the permanent magnet is raised on the horizontal. It is seen from curve 1 of figure 2 that throughout the entire 60 mm displacement of the permanent magnet, two jumps occurred in the magnetic field, i.e., the resistance of the bismuth suddenly drops to almost the zero field value. When the permanent magnet was raised to its highest position, heat was supplied through the manganese-copper wire to destroy the superconductivity of the Nb coils locally. The persistent current decays rapidly. From the deflection of the ballistic galvonometer, which is connected to the pickup coil, one can measure the field strength excited in the lower coil. The persistent current through the coils can be determined from the field strength and the field-current calibration characteristic of the lower coil.

The field-current curve for the lower coil was calibrated at liquid nitrogen temperature. We opened the circuit in figure 1, supplying a constant current from an external source to the lower coil, disrupting this current suddenly, then measuring the corresponding field strength from the deflection of the ballistic galvonometer.

After the superconductivity of the Nb coils was destroyed by the heat from the heating element, the permanent magnet was lowered to its initial position and the experiment repeated. This time, only one jump in the field strength occurred during the raising of the magnet. The position of the jump is located between the two jumps of the previous test (fig. 2, curve 2). Curve 3 of figure 2 is the result of a third repetition of the experiment. When the magnet was raised to the height of about 50 mm, the field in the lower coil reached a strength of more than 2000 Oe. But a field jump took place afterward, and the final value of the persistent current remains very small.

In the fourth and fifth tests, the persistent current increased continually as the magnet was raised, and there was no field jump (curves 4 and 5 of fig. 2). The maximum persistent current obtained with this apparatus was 38 A.

In order for no field jump to occur when the magnet is raised through the total 60 mm, it is necessary to subject the coils to a threefold raising and lowering of the magnet.

The reason for the field jump is contained in the following. With the permanent magnet in the starting position as shown in figure 1, it is inevitable for some of the stray flux of the permanent magnet to be frozen inside the Nb wire (an ideal Meissner effect cannot occur when a hard superconductor is cooled in a magnetic field). This reduces the critical current of the Nb wire. A part of the coil, due to its trapped flux and its incumbency in the stray field of the permanent magnet, acquires a critical current lower than the rest of the coil. When the permanent magnet is raised to a certain height, the superconductivity of this part is destroyed first, causing the field to jump. When the persistent current decays to a very small value, this part of the Nb wire again becomes superconducting. But the original trapped flux was driven out when the superconductivity was destroyed. The new trapped flux in this section of the Nb wire may be lower than the original value, due to the rela- /892
tive displacement between the magnet and the coil. This is why during the next test, no field jump took place when the permanent magnet was raised to the same position. At other sites, however, the trapped flux was not driven out, so that field jumps could still occur. Only after repeating the process could the trapped flux be completely driven out, the critical current of the Nb wire coming close to its normal value and no field jump occurring when the magnet was raised.

This explanation is confirmed by the following experiment. Before liquid helium was transferred into the apparatus, the permanent magnet was first raised to a fairly high position, so that no stray flux could be frozen into the Nb wire. After the transference of liquid helium, heat was supplied through the manganese-copper filament, and the permanent magnet was lowered to its normal initial position as shown in figure 1. Then the experiment was repeated (with the heating element off) by raising the magnet. This time, it was not necessary to run through the preliminary procedure in order to avoid a field jump. Even in the first test, the resistance of the bismuth increased with the raising of the magnet according to a curve like curves 4 and 5 in figure 2.

It is important to note that when the Nb coils are in the superconducting state, the heating element must be turned on before the magnet can be lowered into the upper coil. Otherwise, the permanent magnet can become demagnetized by the reverse field that it creates. In such an experiment, the residual magnetic induction of the permanent magnet after demagnetization was as low as 3200 G. When the thermal power supplied by the manganese-copper wire was high enough that no persistent current was excited by lowering the magnet, the demagnetization was avoided.

If the permanent magnet was raised and then immediately lowered (without allowing the superconductivity to be destroyed by heating), the dependence of the bismuth resistance on the position of the magnet is reversible. In this case, even though the lowering of the magnet reduces the persistent current in the coils, the direction of the field is the same as when the magnet was raised. Thus, demagnetization does not occur. Experimental observation confirms this phenomenon.

By varying the number of turns of the upper and lower coils, the maximum persistent current I_{max} can be varied. Table I shows the results obtained for different numbers of turns in the coils.

It is seen from the results for coils I, II, and III in table I that the persistent current is larger for smaller numbers of turns. Coils III and IV have the same number of turns, but the latter has two layers of Pb-Bi shields each, 0.5 mm thick, between the upper coil and permanent magnet. The shielding

TABLE I				
NUMBER OF TURNS OF THE UPPER AND LOWER COILS AND THE MAXIMUM PERSISTENT CURRENT				
Coil	I	II	III	IV*
Upper coil turns	169	97	24	24
Lower coil turns	174	103	26	26
I_{max}, A	38	68	101	146

*A Pb-Bi alloy shield was installed between the upper coil and permanent magnet.

layers are wound around the core of the coils as shown in the cross-sectional view of figure 3. Their purpose was to reduce the influence of the stray field of the permanent magnet on the Nb coil. The two layers of Pb-Bi alloy were well insulated from one another, so that a closed circuit could not be formed inside the shield. In the experiment with coil III, due to the stray field, a jump in the field occurred when the magnet was raised to a certain height. The maximum persistent current was only 101 A. After the Pb-Bi alloy shield was in place (coil IV), there was no field jump when the magnet was raised and the maximum persistent current had reached 146 A.

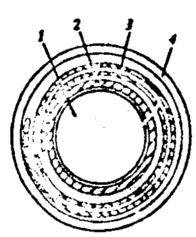

Figure 3. Schematic Diagram, Cross-Sectional View, of the Pb-Bi Shield Between the Coil and Permanent Magnet.

1) Movable Permanent Magnet; 2) Core of the Coil; 3) Pb-Bi Alloy Shield; 4) Nb Coil.

III. DETERMINATION OF THE $I_c(H)$ CURVE

1. Specimen and Apparatus

Figure 4 illustrates the low-temperature section of the experimental apparatus for determining the $I_c(H)$ curve of superconductors. As in the preceding section, the apparatus consisted of a current source, specimen, and detector. /893

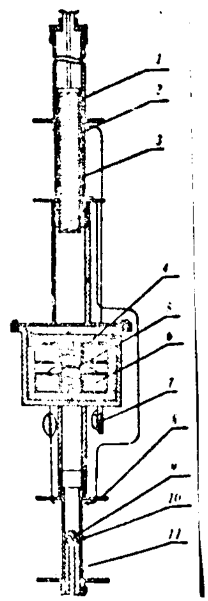

Figure 4. Apparatus for Measuring the Critical Characteristic Curves of Superconductors.

1) Permanent Magnet; 2) Thin Stainless Steel Tube; 3) Core of Upper Coil; 4) Core of Electromagnet; 5) Specimen; 6) Copper Coil; 7) Nb_3Sn Contact; 8) Core of Lower Coil; 9) Bismuth Wire Resistor; 10) Detector Coil; 11) Nb Coil.

The specimen 5 was a segment of cold-worked Nb wire 0.3 mm in diameter and 100 mm in length. A section 4.6 mm long in the middle of the Nb wire was sanded down so that the diameter was reduced to 0.14 mm. The specimen was connected in series with the coils between the terminals of the Nb wires. The connections between the specimen and the coils were made in the same manner as described in the previous section, namely by fusing Nb_3Sn to form superconducting contacts and then coating them with a large quantity of In-Sn alloy. This arrangement ensures that the middle part of the Nb specimen (the section with the 0.14 mm diameter) would be the weakest link of the entire superconducting circuit, and that its critical current would determine the critical current of the circuit.

The external field for measuring the $I_c(H)$ curve was supplied by a small electromagnet 4, 6 placed in the middle of the apparatus. The diameter of the pole pieces was 8 mm, and the distance between the poles was 0.3 mm. Each coil was 8 mm high and had 2000 turns. The current source for the electromagnet was a lead storage battery.

In the actual measurements, the upper and lower coils had 18 and 36 turns, respectively. A Pb-Bi alloy shield was situated between the upper coil and permanent magnet. In order to diminish the flux linking the lower coil relative to the entire frozen-in flux, the inside diameter of the core of the lower coil was reduced to 6 mm. The source of the persistent current, the specimen and electromagnet, and the detector were spaced sufficiently far apart so as to minimize their mutual influence by virtue of stray flux.

2. Method of Measurement

During measurement, the part of the specimen with the smallest diameter was placed between the poles of the electromagnet. The current in the specimen ran perpendicular to the external field.

After liquid helium had been transferred into the apparatus, the permanent magnet was lowered into the upper coil with the heating element on. At this point, the apparatus was ready for the beginning of the measurements. We used two slightly different measurement procedures.

Method I. - At zero field and at several other field strength, the permanent magnet was gradually raised and the resistance of the bismuth resistor simultaneously noted. When the persistent current reached the critical value for that particular field, the resistance of the bismuth stabilized. At this time, the persistent current excited by the continual raising of the permanent magnet decayed spontaneously to the critical current value for the specimen. When the permanent magnet was raised slowly enough, the decay of the current beyond critical did not heat up the specimen to any appreciable extent, and jumps in the magnetic field could be avoided.

The field strength corresponding to the resistance of the bismuth wire was calibrated by means of the pickup coil. The permanent magnet was moved to a definite position, then the bismuth resistance and the deflection of the ballistic galvanometer were read simultaneously as soon as the superconductivity was destroyed by heating. Due to the poor reproducibility of the bismuth resistance during different liquid helium tests, the calibration and the measurement of $I_c(H)$ were accomplished in the same test.

As described earlier, the field-current curve of the lower coil was calibrated separately at liquid nitrogen temperature.

Using the two calibration curves, the critical current $I_c(H)$ of the specimen in the transverse field could be determined from the saturation resistance 894 of the bismuth wire. This procedure is simply illustrated in figure 5.

When the external field was zero or very low, the critical current of the specimen was large and the transition from superconducting to normal very abrupt. Consequently, the approach of the specimen to critical was always accompanied by the occurrence of a field jump. In this case, the given measurement procedure was no longer effective.

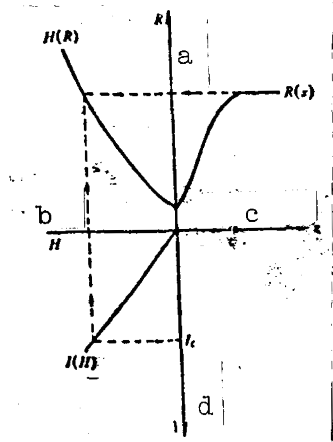

Figure 5. Diagram Illustrating the Method for Determining the Critical Current of the Specimen with Constant Field.

a. Bismuth resistance

b. Field in lower coil

c. Displacement of permanent magnet

d. Current in specimen

Method II. - At zero field and at various other field strengths, the permanent magnet was gradually raised in the upper coil. When the current reached a value such that the specimen was in the critical state, the abrupt transition from superconducting to normal usually caused a jump in the field to occur (the field dropping suddenly to zero). The critical current for the specimen could be ascertained from the deflection of a ballistic galvanometer connected to the pickup coil.

In the strong field region, the critical current was small and the transition from superconducting to normal fairly gradual. Both methods could be used concurrently to determine the critical current $I_c(H)$. The results are in good agreement.

When the permanent magnet was fixed in its position and the current in the coil of the small electromagnet varied, there was no observable change in the resistance of the bismuth. When the permanent magnet was raised to various positions, the superconductivity was destroyed by heating so that the persistent current would decay to zero, the bismuth resistor gave the same resistance value. When the permanent magnet was raised from different starting positions, the measured values of $I_c(H)$ were the same. This demonstrates that the influence of stray fields between the three components of the apparatus is indeed very small.

3. The $I_c(H)$ Curve for Cold-Worked Nb Wire

The critical characteristic curve of cold-worked Nb wire was measured at 4.2°K using the method outlined above. The results are shown in figure 6.

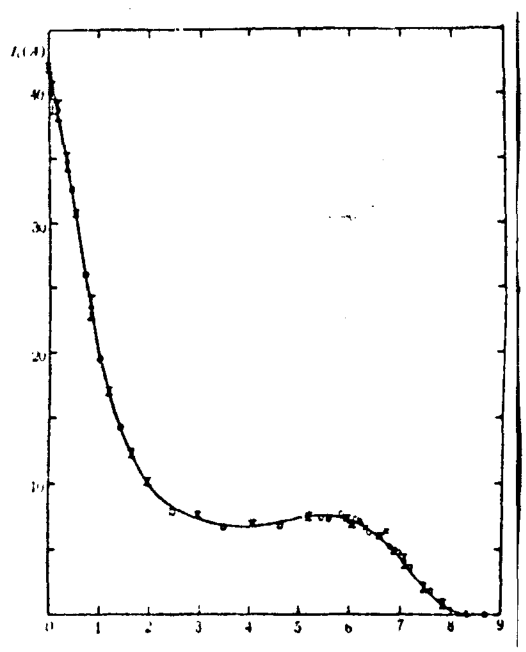

Figure 6. Critical Characteristic Curve for Nb Wire Specimen.

x - 3 July 1964; o - 10 July 1964; □ - 15 July 1964; Φ - Average of Results Measured on 3, 8, 10, and 15 July 1964 with the Same Field; $H \perp I$, $T = 4.2°K$, Diameter of the Nb Wire = 0.14 mm.

The results of four liquid helium tests agree very well, and a single curve can be drawn through all of the experimental points. In the weak field region, the critical current of the Nb wire decreases very rapidly with increasing field strength; when the magnetic field is sufficiently strong, however, a smooth region appears in the curve of critical current as a function of the field. Very much like the first observation of LeBlanc and Little (ref. 11), there is a peak in the $I_c(H)$ curve of Nb. The detailed investigations of DeSorbo (refs. 12 and 13) led to the conclusion that the existence of the peak is related to the nitrogen and oxygen interstitials.

It has been commonly believed that a magnetic field is always harmful to superconductivity. However, the opposite is true when a peak exists in the critical characteristic curve of a superconductor. In this case, the magnetic field may be conducive to superconductivity. Under certain conditions, the magnetic field may drive the specimen from the normal to the superconducting state. This anomalous behavior has elicited some doubt regarding the conventional method of measuring the $I_c(H)$ curve. The curve in figure 6 was measured under persistent current conditions and its physical significance is clear. Consequently, the existence of a peak in the $I_c(H)$ curve may be regarded as conclusively verified, although its mechanism is not quite clear.

IV. DISCUSSION /895

By comparison with the conventional four-probe method, the method described herein has the following advantages:

1. The physical significance of the critical characteristic curve is clear. The experimental points in figure 6 represent the maximum possible superconducting current, or critical current, that can pass through the specimen in the presence of a transverse field. In the four-probe method, the

significance of the critical current is not clear, because it depends on the sensitivity of the measuring instrument. Moreover, the experimental curve refers to states in which superconductivity has already been lost.

2. It circumvents the difficulty of delivering high currents into the cryostate. The current source in figure 1 may also be used in other cryogenic experiments involving superconducting circuits.

3. The specimen is preserved intact. Inasmuch as the internal resistance of the source is zero, the current decays rapidly and automatically when the superconductivity is destroyed, without causing the specimen to burn out. The specimen gives the same experimental results after superconductivity has been destroyed repeatedly. This shows that the specimen is not subjected to any appreciable heat treatment when superconductivity is destroyed.

The apparatus described herein is especially suited to measurements of the characteristics of specimens with large $I_c(H)$. But if the number of turns of the lower coil is increased, or a more sensitive detector is used for the magnetic field, the apparatus will be equally suitable for measuring small critical currents in high fields.

The measurement procedure calls for a constant field to be first supplied by the small electromagnet, then the persistent current to be stimulated. If the persistent current is first excited and the external field varied afterward, the persistent current in the circuit can only decrease with increasing external field, it cannot increase. Consequently, a plateau will appear in the position of the peak.

The key to the effectiveness of the apparatus is in making good superconducting contacts between the specimen and the Nb coils. If the contact is less than ideal, the weak field region of the critical characteristic curve will exhibit a plateau, i.e., the I_c value will remain unchanged as the field is varied.

Alekseyevskiy and co-workers shaped the specimen into a cup (ref. 14) or a coil (ref. 15), then determined the critical characteristic curve of the specimen from the variations of the internal and external fields. Their method does not in principle permit the critical current near zero field to be measured. This is also the region where the four-probe method is technically troublesome.

The frozen-in field has a number of advantages. Its practical use, however, is limited because it cannot be continuously regulated. The field is advantageous only under the working requirement of a constant field, such as in specific heat measurements, adiabatic demagnetization, and certain magnetic resonance experiments. It is important to mention that the current source shown in figure 1 is also a continuously adjustable trapped-flux apparatus. Moving the permanent magnet in the upper coil will continuously vary the field in the lower coil. In our experiment, we obtained a maximum field of 2370 Oe.

Comrade Chang Shou-kung furnished the Alnico-5 permanent magnet used in the experiment. Comrade Li Shih-shu helped with the fusion of the Nb_3Sn contacts. Comrade Li Hung-cheng provided a design for the small electromagnet and participated in some of our discussions. Comrade Hung Chao-sheng critically reviewed the manuscript and offered many fruitful suggestions. To all of these the authors express their utmost gratitude.

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